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This report covers the first six months of a planned, two phase 24 month effort (August 2006 through January 2007). During this period the performance of several types of photonic crystal fibers has been modeled, and an early sample obtained for a glass fiber.

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SEMI-ANNUAL STATUS REPORT

Terahertz Fiber Laser for Explosives Detection

Submitted to:

Department of the Navy, Science and Technology

Office of Naval Research (ONR)

Grant No:

N00014-06-1-0465

By:

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Principal Investigator

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Executive Summary

The C.S. Draper Laboratory, with 30 years of experience in instrument and sensor research and development, and the University of Massachusetts Terahertz Laboratory, with 15 years of research in the development terahertz receivers and focal plane arrays, propose to develop and characterize a **fundamentally new method for generating terahertz radiation.**

Our approach will enable the development of a class of high power (≥100 mW), portable, coherent, terahertz radiation source devices not realizable using either conventional RF approaches such as Schottky Diodes, Transferred Electron Guns, or Resonant Tunneling Diodes or optical transition approaches such as cryogenically cooled Quantum Cascade Lasers.

Consequently, our concept for a **Terahertz Fiber Laser** will enable a US Navy **Advanced Explosives Detection** system with significantly improved sensitivity, selectivity, and >20m stand-off operating range in a compact (shoebox size), man-portable package.

Fundamentally New Approach for Generating THz Radiation

Fills Critical THz Source technology gap

- **0.5 – 4.0 THz**
- **High Power (>100mW)**
- **Room Temperature**
- **Portable**

Enables Advanced Explosives Detection

- **> 20 m stand-off**
- **Improved sensitivity**
- **Improved selectivity**
- **Non-Ionizing (Safe)**

This report covers the first six months of a planned, two phase 24 month effort (August 2006 through January 2007). During this period the performance of several types of photonic crystal fibers has been modeled, and an early sample obtained for a glass fiber. Although, as originally proposed, initial analyses, indicated promise for glass fibers, subsequent more detailed modeling identified some previously unanticipated material-related losses. Fortunately, the same analyses and models have pointed towards an extremely promising hollow plastic fiber approach

Unlike glass, plastic materials show significantly lower transmission losses in the THz regime. Furthermore, several research groups have demonstrated THz waveguiding in hollow, plastic optical fibers. Our goal to produce an efficient (≥100 mW) optically pumped THz laser for use in explosives detection continues to look reasonable based on available fiber data. During this same period, it was necessary to replace the previous Principal Investigator (PI), Dr. Hakimi, who decided to leave Draper Laboratory. Fortunately, a new PI, Dr. Radojevic, has assumed technical direction of the program with negligible impact the the two-year plan.

Overview of Research Efforts During Phase I

Initial Glass Fiber Approach

During these first six months of Phase I, Draper Laboratory has performed extensive computational simulation of various fiber structures using a state-of-the-art beam propagation software package. The goal of this effort was to identify Photonic Crystal Fiber (PCF) candidate structures that could be used for generation of THz radiation with aims at utilizing the proposed SRS effect in glass fiber (Figure 1).

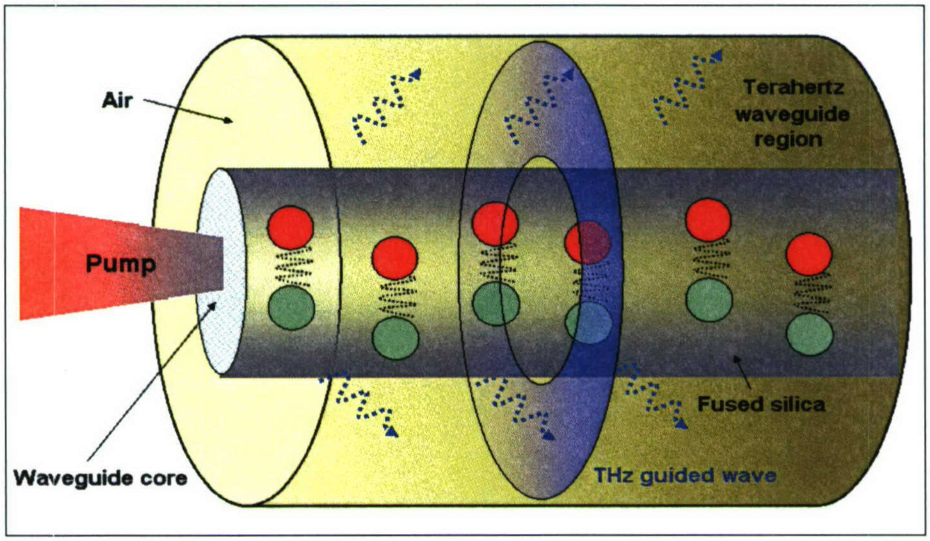

Figure 1 Original approach to generating THz radiation for optical fibers. The pump interacts with the fused silica material, generating a Stokes-shifted signal, several THz offset from the pump. The energy lost to the offset is expected to radiatively couple in the guided modes of the glass fiber structure and propagate mostly in air.

Due to the nature of the SRS effect, the main goal of the design effort was to come up with structures that would support guiding in glass structures at the pump and the idler wavelengths, and, at the same time, air guiding the THz photon modes. In fact, it is critical that THz photons not propagate through the glass material, as this would result in prohibitively high losses (~ dB/μm in the THz) that would be extremely difficult to overcome with any possible SRS gain.

In the early stages of design, an opportunity presented itself to procure a specialty fiber that could be used in the THz regime, with little lead time and at a fraction of the cost of what had been originally anticipated, a total of 48 meters of fiber was procured from Stocker Yale. Detailed modeling and design analysis has shown that although this particular fiber meets the initial design goals, any glass fiber would still exhibit very high losses at THz wavelengths, because a significant portion of the fundamental THz mode would still see the glass core, as shown in Figure 2.

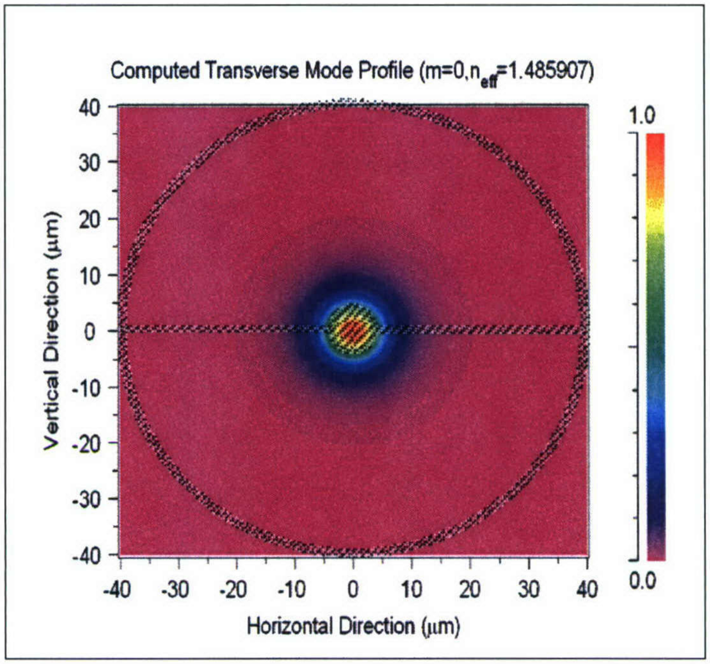

Figure 2 Computed transverse mode profile at 12THz for a glass fiber structure procured from Stocker Yale. Note that a significant portion of the guided mode remains in the highly lossy glass material. The shaded area represents glass fiber (the pink is hollow).

Because this result was in contradiction with our earlier expectations, we have engaged several outside THz experts to assist in assessing the amount of THz gain that could be expected from the SRS process in glass fibers. Among others, we have discussed this matter with Professor Tony F. Heinz of Columbia University in New York City and Professor Michael Hasselbeck of the University of New Mexico in Los Alamos, both of whom have been very active in the field. Their feedback confirmed our simulation results. Due to the non-polar nature of fiber glass material and the fact that SRS in such media is predominantly Raman-active and only weekly IR-active, the amount of gain available from the SRS process in glass materials would be too small compared to propagation losses to establish the necessary gain. Hence, our decisions to redirect our efforts, abandon the glass fiber approach, and pursue plastic optical fibers as waveguiding media.

Alternative Plastic Fiber Approach

Optically-pumped gasses have been used for for several decades to generate Terahertz radiation. Efficient bulk tabletop sources have been demonstrated and employed in many important applications. These sources are capable of producing 10s of mW of coherent THz optical power. The principle of THz generation in THz active gasses is schematically shown in Figure 3, where methanol vapor pumped with a CO_2 laser is used as an example. Here, the mid-IR optical pump excites a higher vibrational level of the active medium, within

which a population inversion is created between a higher and lower (ground) rotational level. This population inversion is followed by a radiative decay from the higher to the lower rotational level and emission of photons at far infrared frequencies. The de-excited electrons then nonradiatively decay to the ground vibrational level and the whole process starts over again.

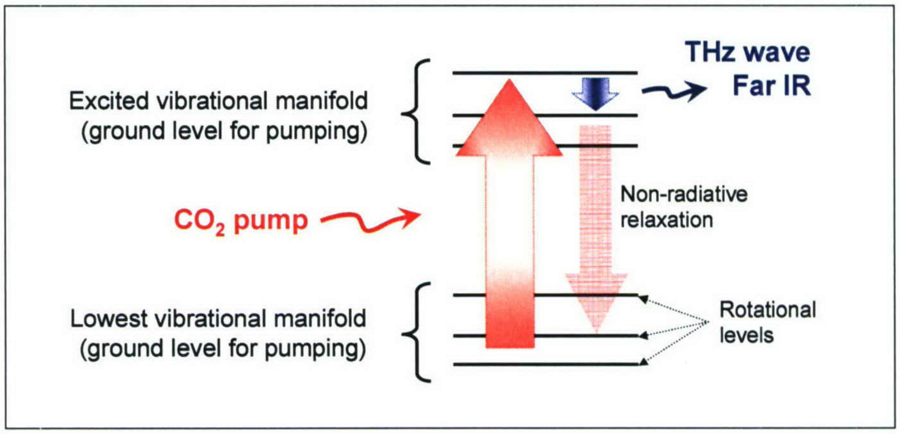

Figure 3 Energy diagram and transitions in a THz active medium such as CH_3OH.

What sets our approach apart from the existing implementations is the use of a gas-filled hollow-core PCF (HCPCF), designed to support both pump and THz wavelengths. The use of a fiber rather than bulk structures essentially enables for fabrication of more compact and efficient stand-off portable THz laser sources. The main idea behind this approach is that the HCPCF fiber can be designed and manufactured such that it simultaneously supports low-loss guided of waves at both pump and THz wavelengths. A transfer function of such a fiber is graphically shown in Figure 4.

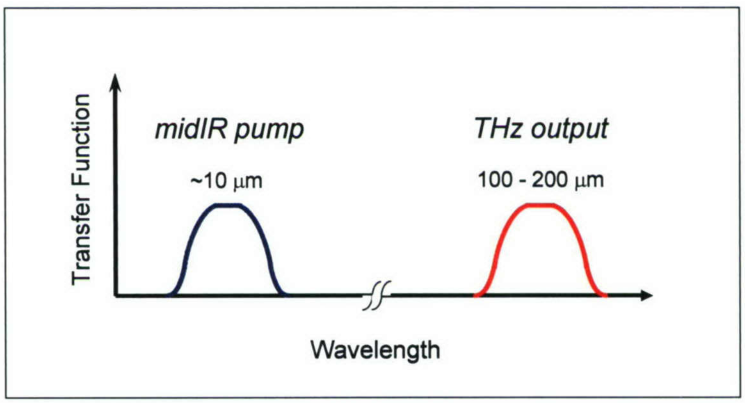

Figure 4 Desired transfer function of a HCPCF fiber.

According to the well known Manley-Row limit, the maximum expected conversion efficiency from the pump to the THz wavelengths is ~ $f_{THz}/(2 \times f_{pump})$,

which in our case results ~4%. Given that compact CO_2 pump laser sources are available at pump powers of ~10 W, with the assumption that coupling and propagation losses in the proposed gas-filled fiber resonator can be controlled and minimized, a 100 mW power output at THz wavelengths seems achievable.

There are some risks to this new proposal:

- Design of the PCF fibers that guide both the pump and the THz wave with minimal losses, adequate for efficient THz lasing, is critical. While separate guiding has been demonstrated, simultaneous propagation is yet to be realized.
- Gas filling of PCF fiber and creation of a laser cavity with suitable properties is another challenging part of this undertaking.
- THz generation in gas-filled photonic crystal fibers has not been demonstrated yet.
- Engineering of coupling and reflective structures that allow for efficient and tailorable manipulation of distant wavelengths.

To mitigate the risk, we are considering partnering with some of the university research groups whose work is at the cutting edge of research in this field. To this date, we have identified two such groups.

The first group is the Advanced Photonics Structures Group from Montreal, Canada, at the Ecole Polytechnique du Montreal, which has developed a new way of fabricating Bragg photonic crystal fibers out of plastic materials. The Brag grating embedded in the plastic material that surrounds the hollow core makes this design particularly attractive as multiple gratings can be superimposed to result in a transmission profile (i.e. transfer function) as that shown in Figure 4. This approach is particularly attractive in this case as the large wavelength separation between the supported bands should theoretically allow for somewhat relaxed design-fabrication trade-offs.

The second group is with the Optical Fiber Technology Center in Sydney, Australia, at the University of Sydney, which has experience in the fabrication of hollow core fibers in plastic. This group has developed a fabrication process for microstructured polymer optical fibers fabricated from commercially available PMMA. The modus operandi is similar to that seen in glass PCF fibers via photonic bandgap guidance.

Although the above two groups are not from the United States, given their experience and expertise in the area of plastic HCPCF, we find it quite important to try and partner with them in this project. This, however, will not preclude us from continuing our search for U.S. based partners in this area of research.

Some examples of plastic HCPCF fibers are shown in Figure 5 and Figure 6.

Waveguiding at THz wavelengths has already been demonstrated in plastic fibers. Propagation loss in plastic fibers is significantly lower than in glass fibers (~5 dB/m in plastic vs. ~1 dB/μm in glass). The existence of table-top THz gas laser sources together with a low propagation loss of plastic fibers in the THz

regime lead us to conclude that gas-filled HCPCF approach provides more opportunity for success than the originally proposed SRS.

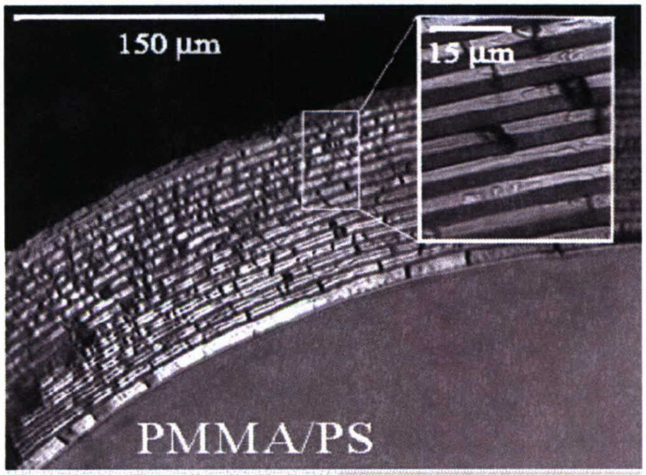

Figure 5 Example of a plastic hollow-core Bragg grating photonic crystal fiber made by the Advanced Photonics Structures Group in Montreal, Canada.

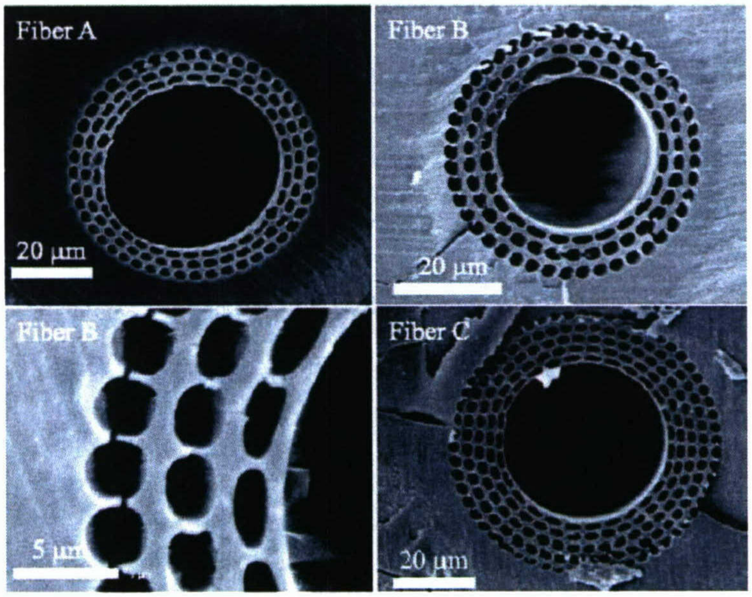

Figure 6 Scanning electron micrographs of hollow-core plastic photonic crystal fibers produced by the Optical Fiber Technology Center in Sydney, Australia.

Experimental Plans

Draper will work on the design and manufacture of the plastic HCPCF fibers, to support low-loss propagation of both the pump and the THz wavelength radiation. The voids (holes) inside the plastic photonics crystal fiber will be filled with a suitable THz-active gas (e.g. acetylene, which has commonly been used as an active THz medium). Optical pumping will be by an adequate, gas-matched laser source in the mid-IR wavelength region (in the case of acetylene, a high-power and compact CO_2 laser would be used as the pump). The HCPCF fiber will be a part of an optical resonator in the THz wavelength range, which will be formed by means of external optical couplers and reflectors at fiber input and output, as shown in Figure 7. The input midIR coupler will allow for efficient coupling of the pump wave. The input THz reflector will be designed to have as high a reflectance at THz as possible. The output THz coupler will be designed to provide for optimal laser efficiency. In order to enhance the overal system efficiency, the resonator may be designed so as to provide for additional pump reflection at HCPCF fiber input and output.

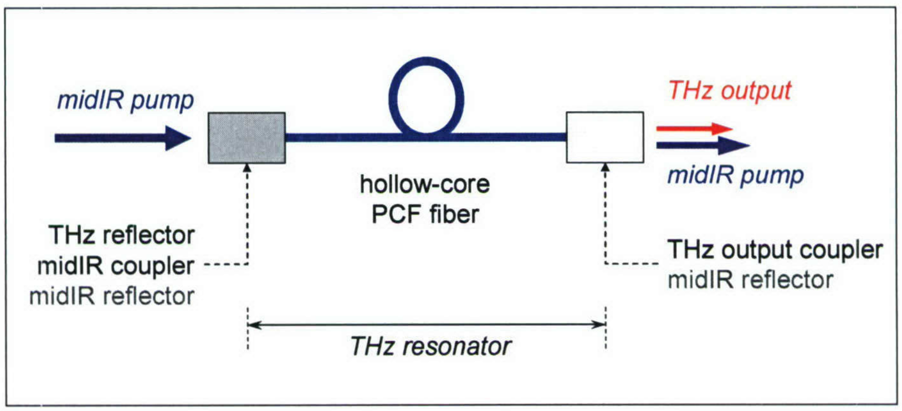

Figure 7 Schematic layout of a hollow-core plastic PCF fiber THz laser. The two gray boxes at fiber input and output represent integrated beam delivery systems for the pump and THz wavelengths. The hollow core PCF fiber is filled with a THz-active gas.

This investigation remains divided into five stages:

- <u>Stage 0.</u> Conceptual design and preliminary modeling - Complete
- <u>Stage 1.</u> Design, manufacture, and characterization of plastic HCPCF fibers.
- <u>Stage 2.</u> Generation of coherent THz radiation from a plastic HCPCF fiber filled with a TH-active gas.
- <u>Stage 3.</u> Demonstration of a prototype optical-bench fiber THz laser based on a gas-filled HCPCF.
- <u>Stage 4.</u> Demonstration of a compact prototype THz laser based on a gas-filled HCPCF.

We will continue our collaboration with the Terahertz Laboratory of the University of Massachusetts (UMTL), to perform evaluation of output power, spectra, spatial mode, and stability in the THz regime.

Detailed Plan

The four stages (1-4) described above can be further broken down into more detailed tasks, which are expected to progress as shown in below. Although at this time there are only two known likely potential sources for appropriate hollow core plastic fiber, our material investigations and research will continue and if additional alternatives are identified, evaluations will be performed to the greatest extent possible within financial and schedule constraints.

The HCPCF fiber is a new product and the use of these fibers to generate narrowband high intensity terahertz radiation holds significant promise. It is anticipated that both fiber products and system concepts will mature and improve based on feedback of test results. A secondary goal of this effort is to establish evaluation equipment and processes with appropriate controls and repeatability for use in the improvement spiral.

<u>Stage 1.</u> Design, manufacture, and characterization of plastic HCPCF fiber

a) Design of several candidate plastic HCPFC fibers
estimated duration: 3 months.

b) Manufacture of prototype plastic HCPCF fibers
estimated duration: 2 months.

c) Characterization of prototype plastic HCPCF fibers at optical and THz wavelengths (waveguiding, modal properties, transmission loss and spectra, etc.)
estimated duration: 1 month

d) Design optimization based on characterization results
estimated duration: 1 month

e) Optimization of the manufacturing process based on characterization results.
estimated duration: 2 months

<u>Stage 2.</u> Generation of coherent THz radiation from a hollow-core plastic PCF fiber filled with a TH-active gas

a) Design and realization of coupling structures for THz and optical
estimated duration: 2 months

b) Setup of test apparatus demonstration of THz generation from gas-filled HCPCF fibers
estimated duration: 2 months

Stage 3. Demonstration of a prototype table-top fiber THz laser based on a gas-filled HCPCF fiber

a) Design and realization of coupling structures
estimated duration: 3 months

b) Setup of table-top THz laser
estimated duration: 1 month

c) Testing, characterization
estimated duration: 1 month

d) Design refinement
estimated duration: 1 month

Stage 4. Demonstration of a compact prototype THz laser based on a gas-filled HCPCF fiber

a) Component design, miniaturization, and realization of a compact prototype gas-filled THz laser based on results from Stage 3
estimated duration: 4 months

b) Testing, characterization, design refinement
estimated duration: 3 months

Financial Status

Expenditures and outstanding commitments are summarized below.

ThZ Fiber Laser (20673) Bi-Annual Financial Report

	ITD Jan 07	ITD Aug 07	ITD Jan 08	ITD Aug 08	Total
Labor	59,529				59,529
Non-Labor	12,306				12,306
Total	**71,835**				71,835
Outstanding Commitments	34,600				
Total w/Outstanding Commitments	**106,435**				**106,435**
Funded Amount	299,684				299,684
Balance Remaining NOT including OSC	227,849				227,849
Balance Remaining including OSC	193,249				227,849
Total Grant Value	629,044				
Funded Amount To Date	299,684				
Amount Remaining to be Funded	329,360				

Activity Name	Start Date	Finish Date
Approach Definition		
System Approach Definition	8/6/07	2/15/08
Fiber concept	10/1/07	5/2/08
Fiber source identification		
Identification and evaluation of Fiber alternatives	7/30/07 7/14/08	6/27/08 7/10/09
Design of several candidate hollow-core plastic photonic crystal fibers.	5/5/08 11/17/08	10/31/08 7/10/09
Manufacture of prototype plastic hollow-core PCF fibers.	8/4/08 2/16/09	2/6/09 7/10/09
Fiber testing		
Characterization of avaliable fibers	6/30/08 10/13/08	10/3/08 7/10/09
Characterization of prototype PCF fibers at optical and THz wavelengths.	10/6/08 4/6/09	3/27/09 7/10/09
Design optimization. Optimization of the manufacturing process.	1/5/09 6/8/09	5/29/09 7/10/09
Laser Assembly and Test		
Demonstration of THz radiation generated from optically-pumped gas-filled plastic PCF fibers.	3/2/09	7/3/09
Demonstration		
Lab demonstration of lasing action in the THz regime in gas-filled plastic PCF fibers.	3/30/09	7/10/09
Demonstration of a prototype THz laser	7/20/09	
Reports		
Technical Status	2/25/08